Muon Collider - Open Questions and New Ideas

July 20, 2020

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Muon Collider Collaboration

- June 19, 2020 the Eu Strategy updated was published, where at page 14en, we read:
  […] In addition to the high field magnets the accelerator R&D roadmap could contain: ***an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e^+e^- colliders, and potentially within a more compact circular tunnel than for a hadron collider.*** *The biggest challenge remains to produce an intense beam of cooled muons, but novel ideas are being explored;[…]*
- To facilitate the implementation of the EU Strategy the CERN Laboratory Directors Group on July 2nd:
  - Agreed to start building the collaboration for international muon collider design study.
  - Daniel Schulte appointed ad interim project leader, Nadia Pastrone, Lenny Rivkin and Daniel Schulte will collect MoUs.
- Scope:
  - develop a baseline concept for a muon collider at centre-of-mass energy ranges: 3-10 TeV or above
  - identify an **R&D path** toward a conceptual design;
  - design a **demonstrator**.

International Muon Collider Collaboration kick-off virtual meeting on July 3rd

https://indico.cern.ch/event/930508/

First collaboration meeting on Physics and Experiments at a Muon Collider

On **July 27th** there will be a remote meeting, here the link to the agenda, to discuss:

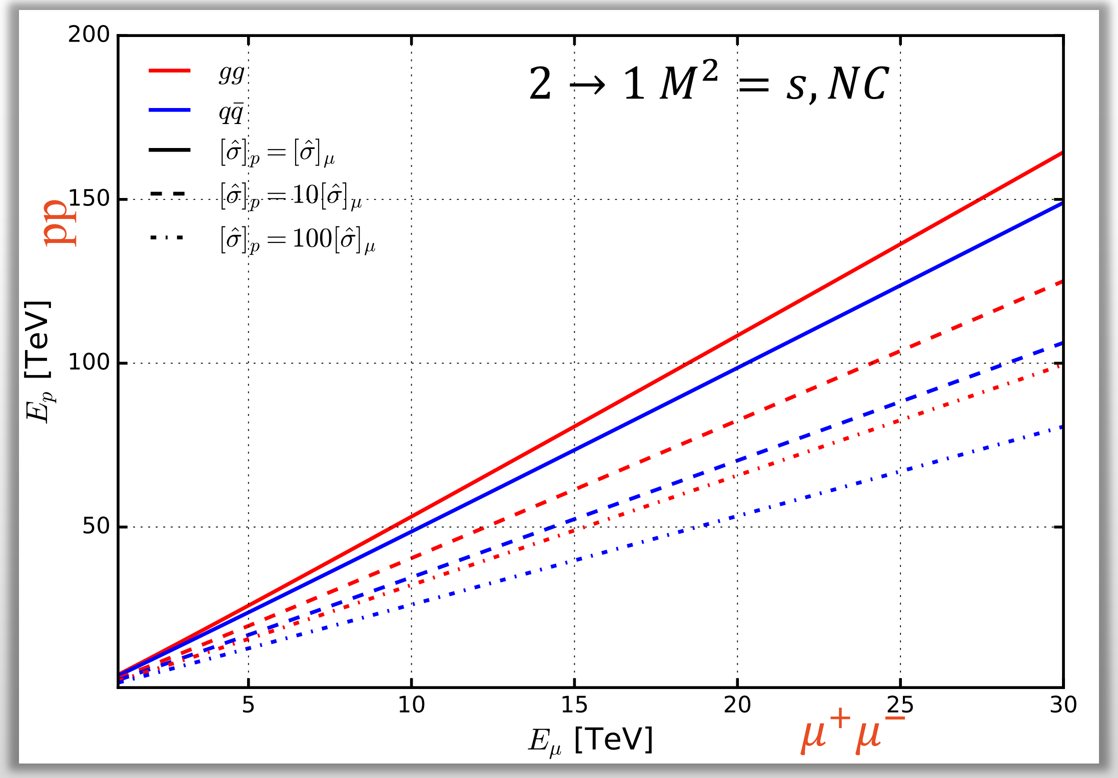
- Physics benchmarks at 3 TeV and 10+ TeV center-of-mass energy to have a multi-TeV muon collider physics reach:
  - Agree on a set of physics processes to better coordinate the studies in the next months
- Detector performance in the presence of the beam-induced background at different center-of-mass energy:
  - Selection of R&D that can be performed in synergies with the upgrade of existing experiments and new projects.
  - Identification of brand new R&D specific to the project.
- Software framework to perform the studies:
  - On July 16en an hands-on on the current code version has been performed at Fermilab by M. Casarsa, here the link to the slides .

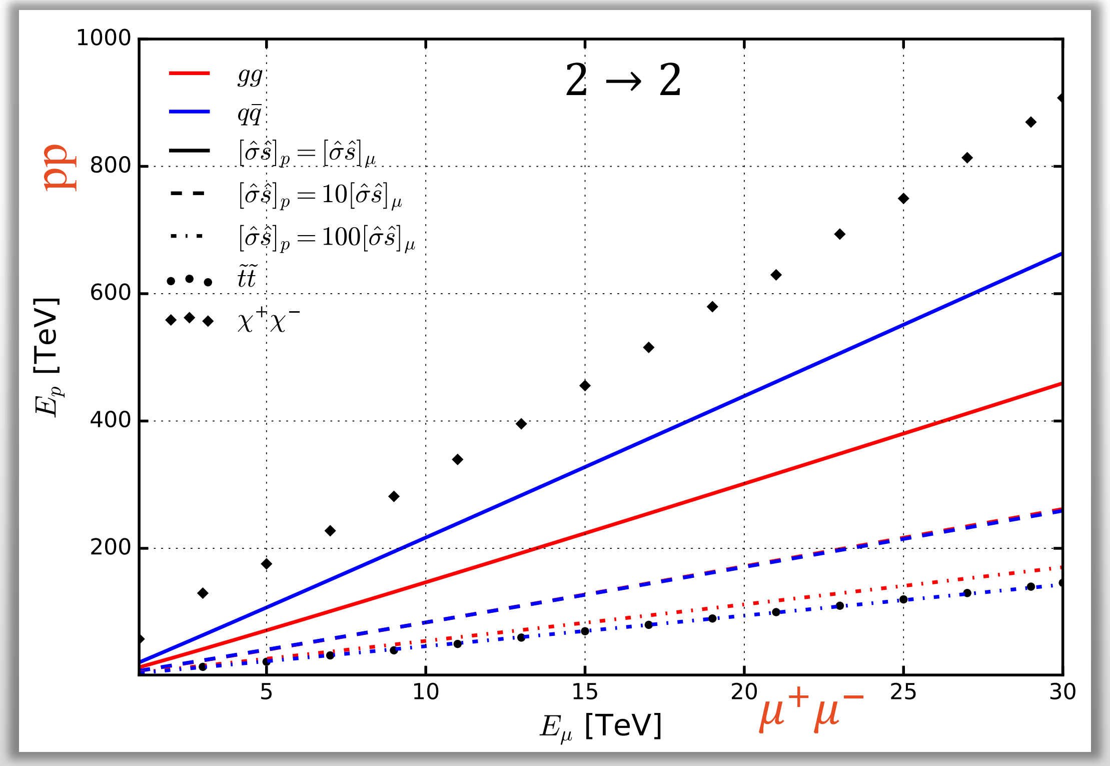
Please, register to the meeting if interested.
A document with a proposed plan for discussion is in preparation and will be linked to the agenda.

Physics Motivations: Discovery Potential

The advantage in colliding muons rather than protons is that $\sqrt{s_\mu}$ is entirely available to produce short-distance reactions. At a proton collider the relevant interactions occur between the proton constituents, which carry a small fraction of $\sqrt{s_p}$

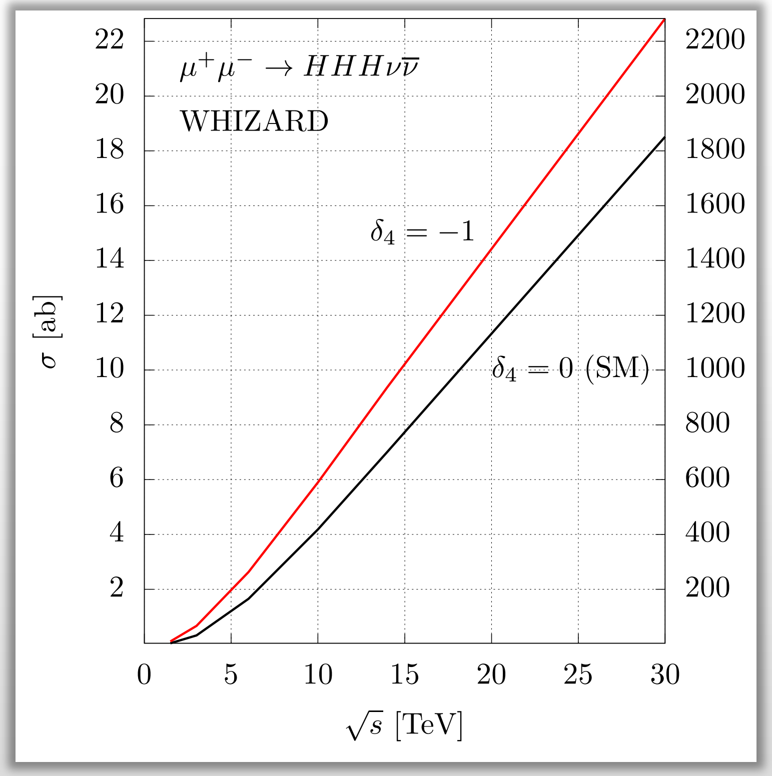
Vector boson fusion at multi-TeV muon colliders, A. Costantini *et al.*





Physics Motivations: Discovery Potential through the Higgs Boson

Higgs boson couplings to fermions and bosons reaches have to be evaluated, similar or better performance of e^+e^- are expected. In addition, muon collider has the unique possibility to determine the Higgs potential having sensitivity also to quadrilinear coupling



$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

$$\lambda_3 = \lambda_{SM}(1 + \delta_3)$$
$$\lambda_4 = \lambda_{SM}(1 + \delta_4)$$

Muon Collider with several TeV CM energy and with integrated luminosities of the order of several tens of attobarns, could provide enough events to allow a determination (a SM) quartic Higgs self-coupling with an accuracy in the tens of percent.

Measuring the quartic Higgs self-coupling at a multi-TeV muon collider, M Chiesa *et al*.

Physics Studies

The Physics Briefing Book prepared for the European Particle Physics Strategy Update (EPPSU) includes many physics studies with lepton collisions up to $\sqrt{s} = 3$ TeV for CLIC. Muon collider is not part of it because it did not exist at that time.

Muon Collider cases:

- Physics studies at $\sqrt{s} = 3$ TeV, equal or similar to what has been done for EPPSU. Since the running conditions are different the physics reach are expected to be different.

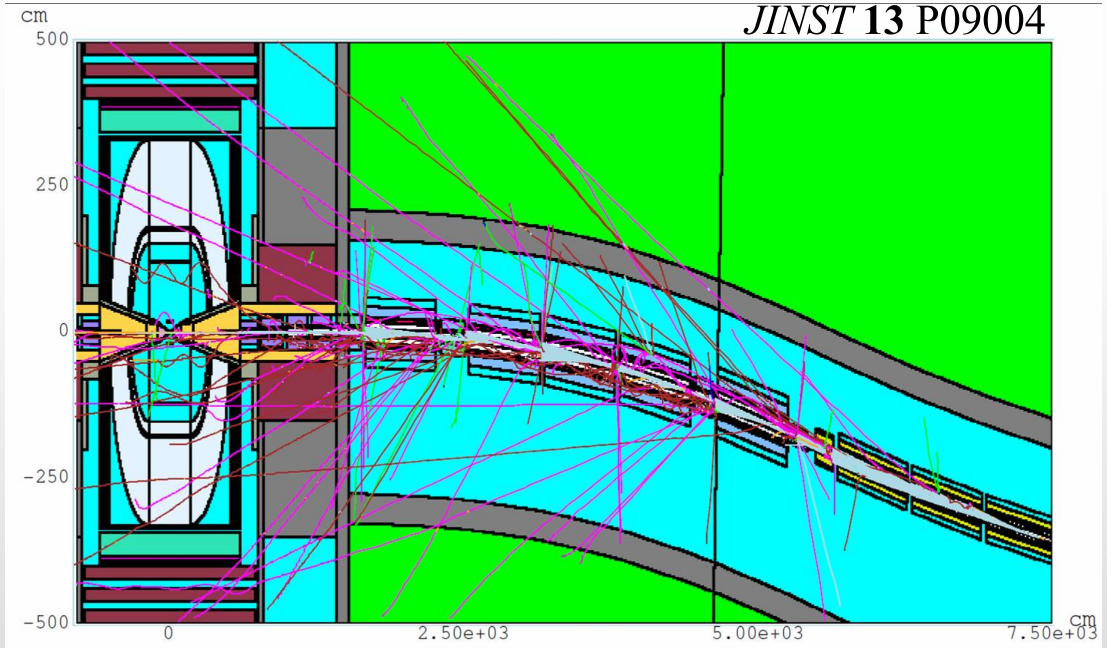
- Physics studies at $\sqrt{s} = 10 +$ TeV are almost new:
  - Perform the relevant studies done for other collider for EPPSU in the new energy regime.
  - Identify the new physics possibilities that open up at high energy.

- Verify the software availability for the physics signals and the physics background.
  - The beam-induced background plays a special role, it will be discuss later.

The Challenge: beam-induced background

Muon induced background is critical for:

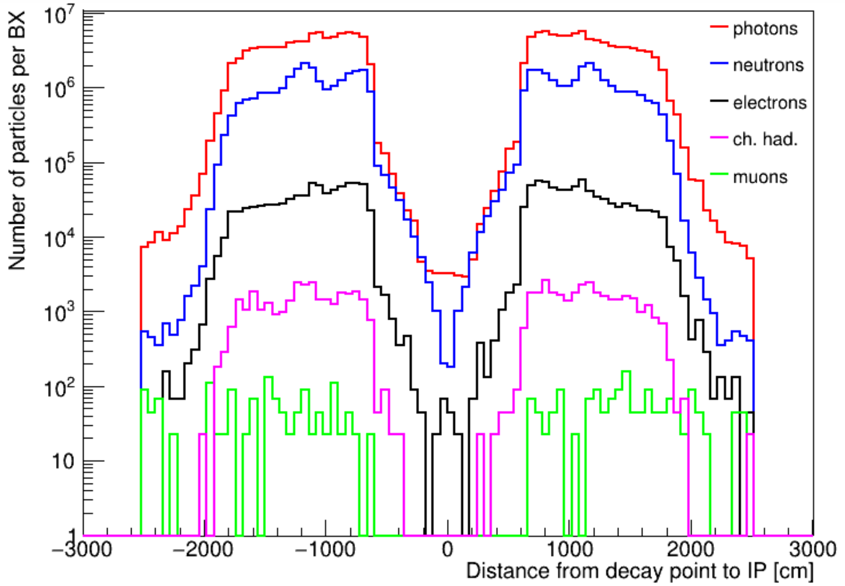
- Magnets, they need to be protected
- Detector, the performance depends on the rate of background particles arriving to each subdetector and the number and the distribution of particles at the detector depends on the lattice

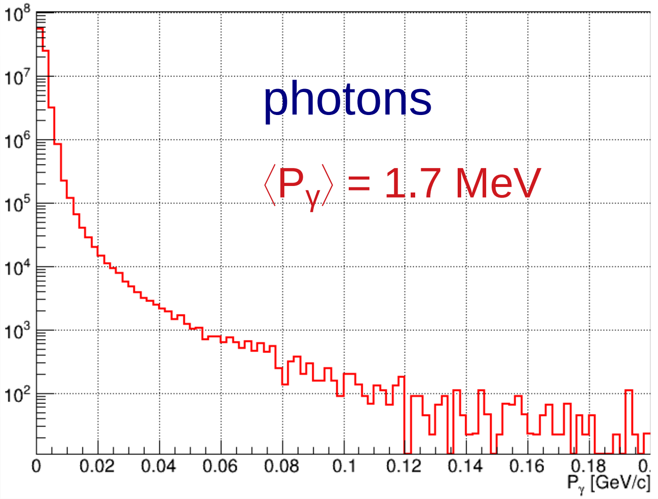


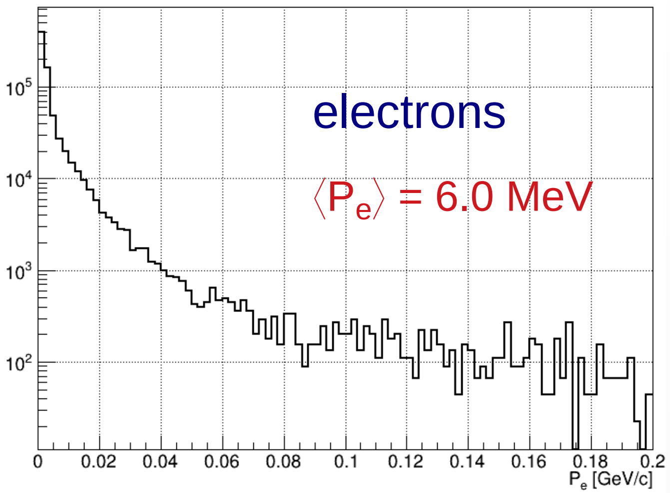
JINST **13** P09004

- MAP developed a realistic simulation of beam-induced backgrounds in the detector by implementing a model of the tunnel and the accelerator ±200 m from the interaction point.
- Secondary and tertiary particles from muon decays are simulated with MARS15 then transported to the detector.
- Two tungsten nozzles play a crucial role in background mitigation inside the detector.

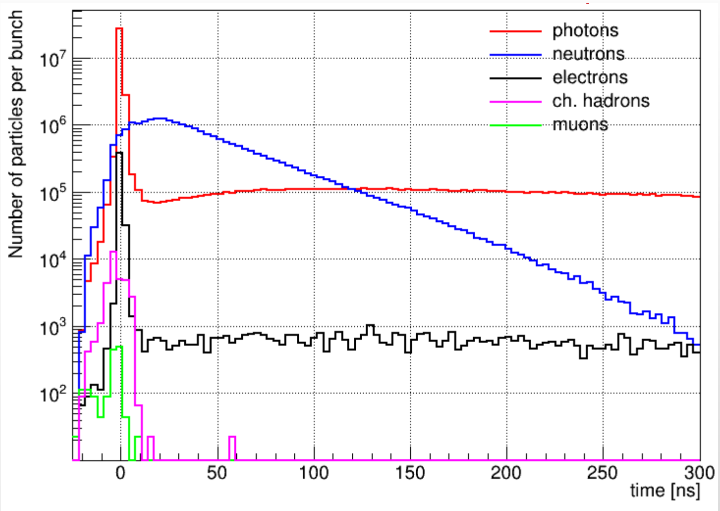
Beam-induced background properties for 750 GeV $\mu^{\pm}$ beams





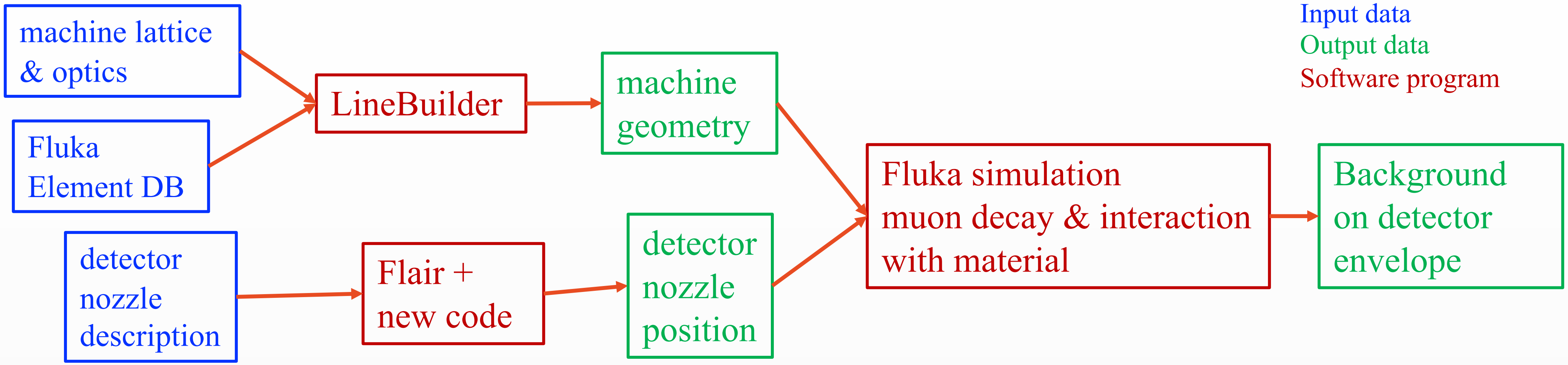


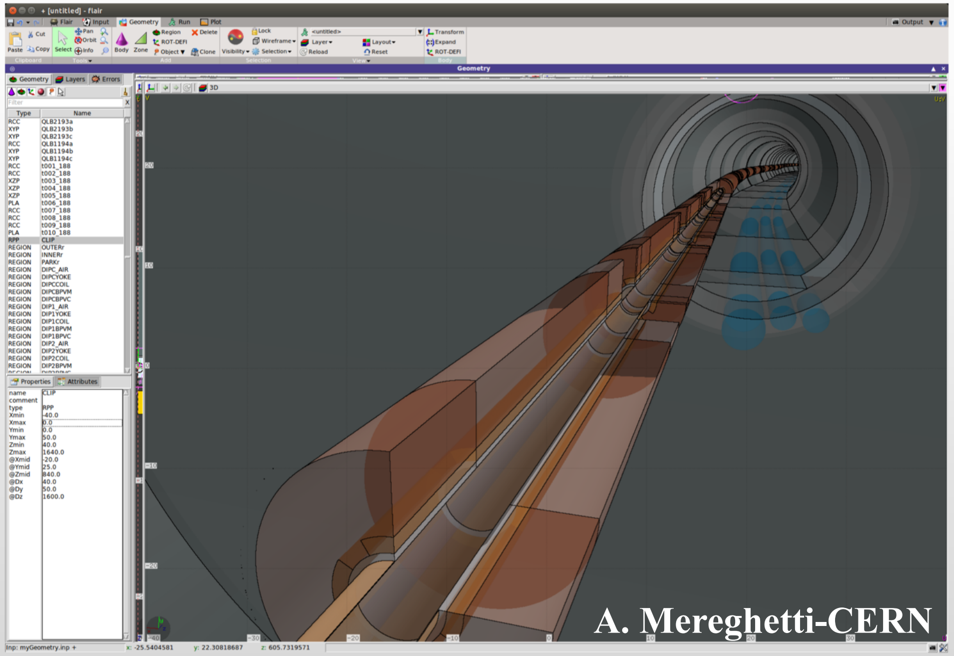
Contributions form μ decays |z| > 25 m become negligible for all background species but Bethe-Heitler muons



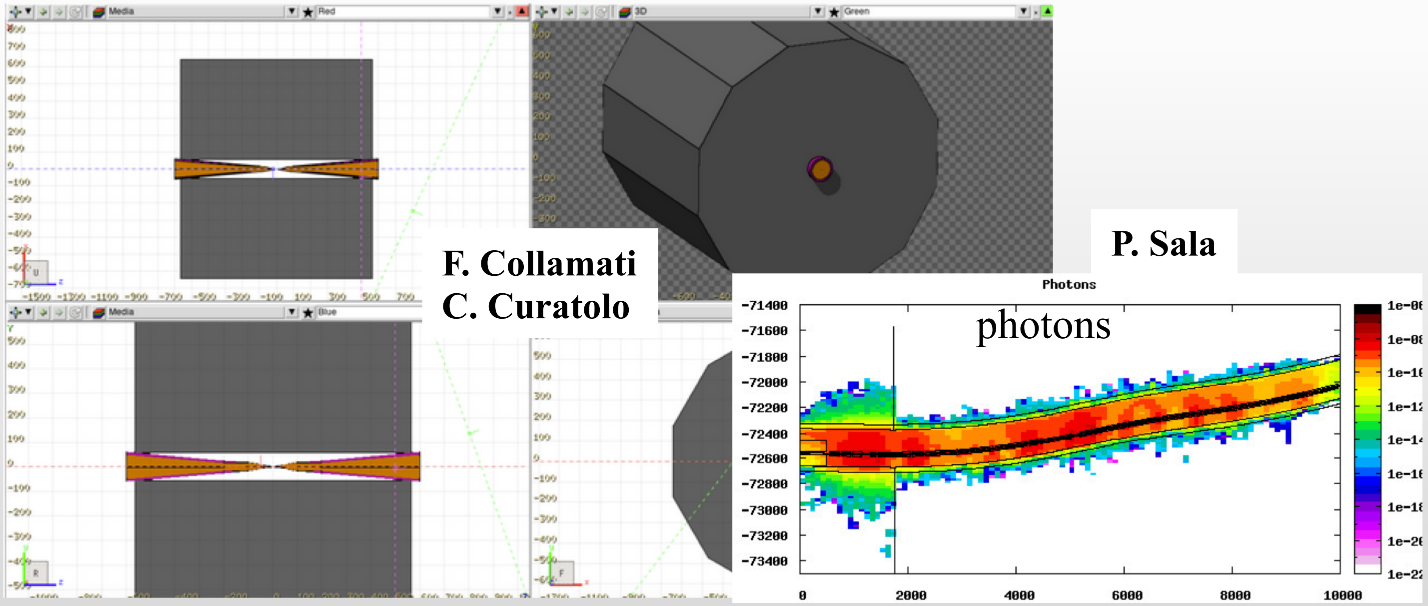
Secondary and tertiary particles have low momentum and different arrival time in the IP.

The beam-induced background simulation





A. Mereghetti-CERN



F. Collamati
C. Curatolo

P. Sala

Beam Induced Background Studies

Possible working plan and collaboration:

- The software necessary to perform beam-induce-background (BIB) studies is ready.

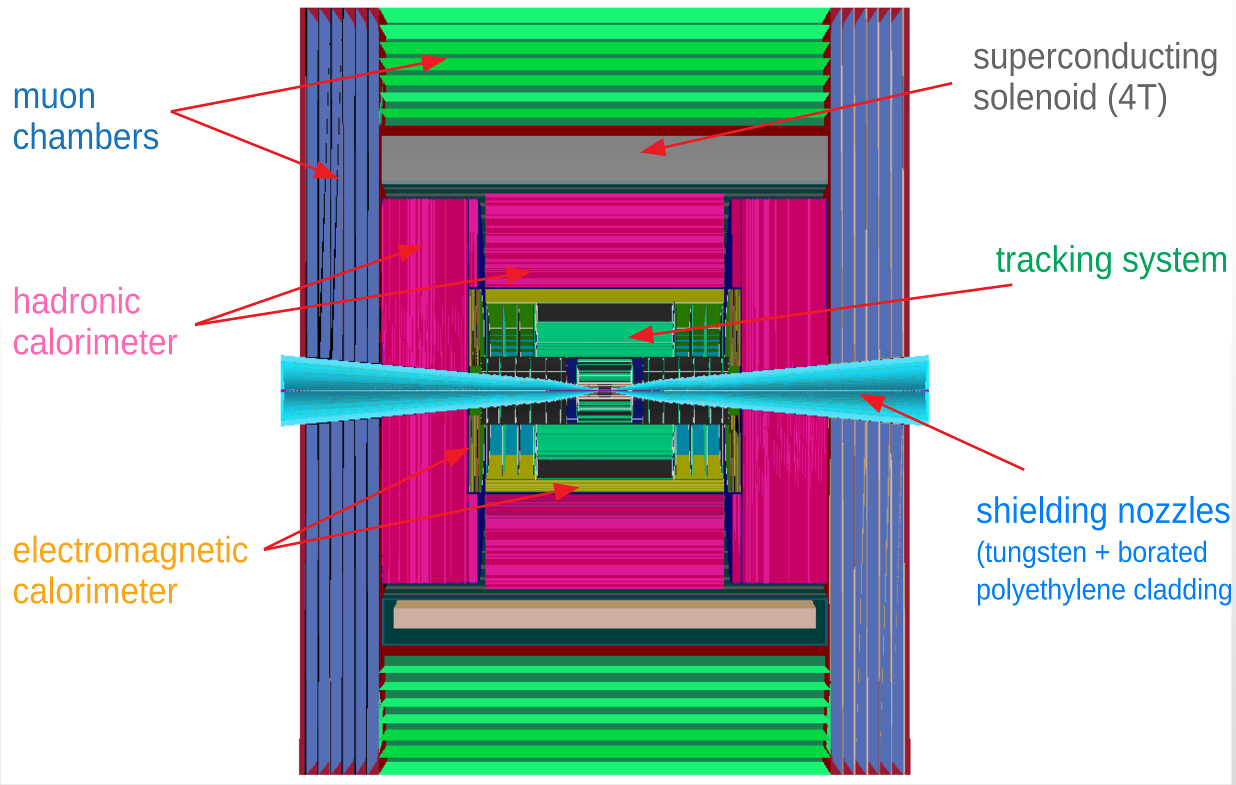
- The BIB can be studied and characterized at different center-of-mass energies:
  - $\sqrt{s} = 1.5$ TeV is what was available from MAP, used to test the full software chain, thanks to MAP collaboration for providing the machine lattice and optics.

  - $\sqrt{s} = 3$ TeV is the next step, machine lattice and optics are needed, it should be available from previous MAP activities. Some work may be needed. The "nozzle" shape and material has to be optimized or other mitigation strategies have to be studied.

  - $\sqrt{s} = 10$ TeV the machine lattice and optics are missing… difficult to have it in a year time scale. Discussion with accelerator experts to understand if and how to proceed.

Study of Detector Response at $\sqrt{s}$ =1.5 TeV

The simulation/reconstruction tools supports signal + beam-induced background merging.
ILCSoft, which will be part of the Future Collider Framework, Key4hep, is used.



CLIC Detector adopted with modifications for muon collider needs.
Detector optimization is one of the future goal.

Vertex Detector (VXD)

- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks ”

Inner Tracker (IT)

- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)

- 3 barrel layers 50x50μm^2
- 4+4 disks ”

Electromagnetic Calorimeter (ECAL)

- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

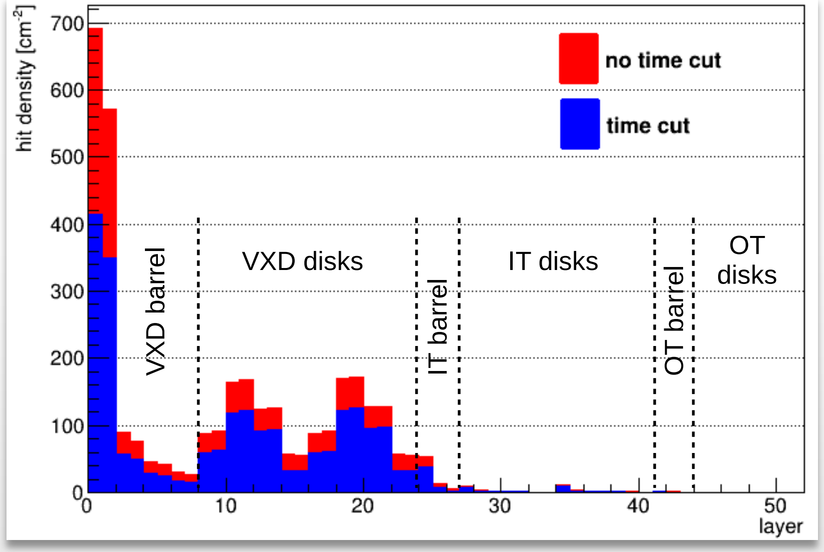
Hadron Calorimeter (HCAL)

- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

Tracking performance at $\sqrt{s}$ =1.5 TeV

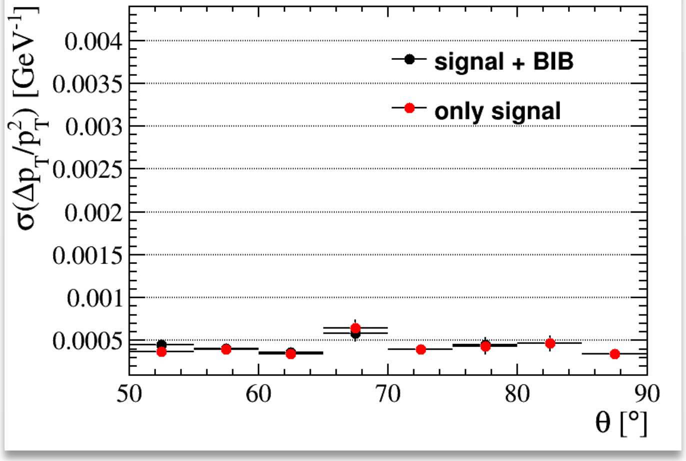
L.Sestini M. Casarsa N. Bartosik L. Buonincontri

Effects of beam-induce background can be mitigated by exploiting "5D" detectors, i.e. including timing.

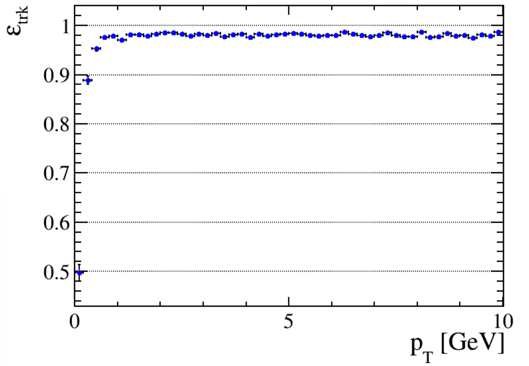


- Simplified digitization: position + time smearing. Realistic digitization in progress.
- Double-layer based BIB rejection in progress.

Track momentum resolution

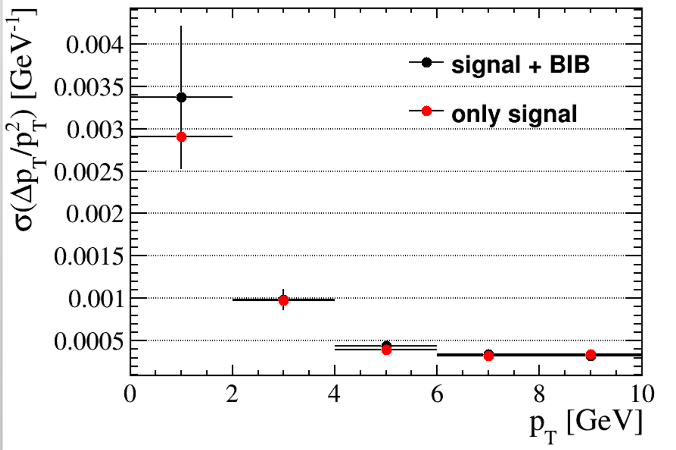


Track momentum efficiency

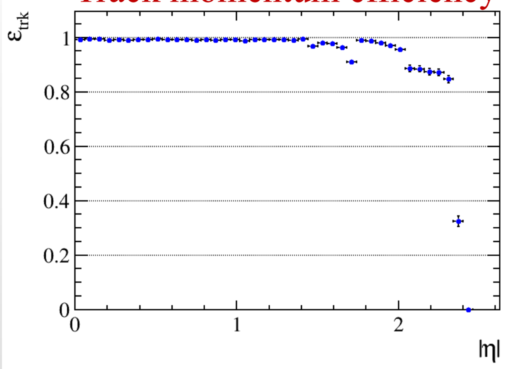


Signal=muon gun

Track momentum resolution



Track momentum efficiency



Calorimeter performance at $\sqrt{s}$ =1.5 TeV

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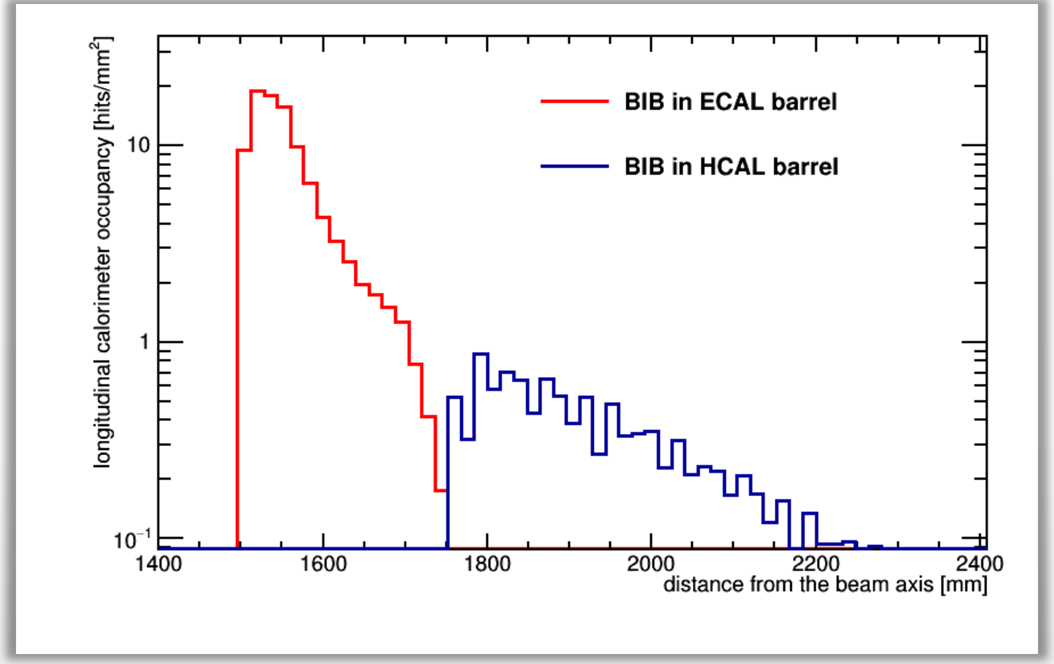
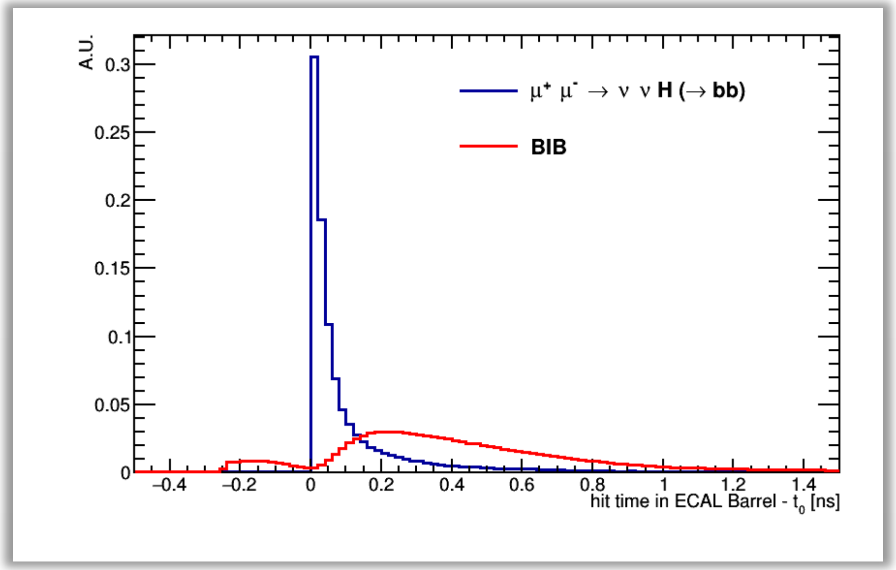
Calorimeter Occupancy

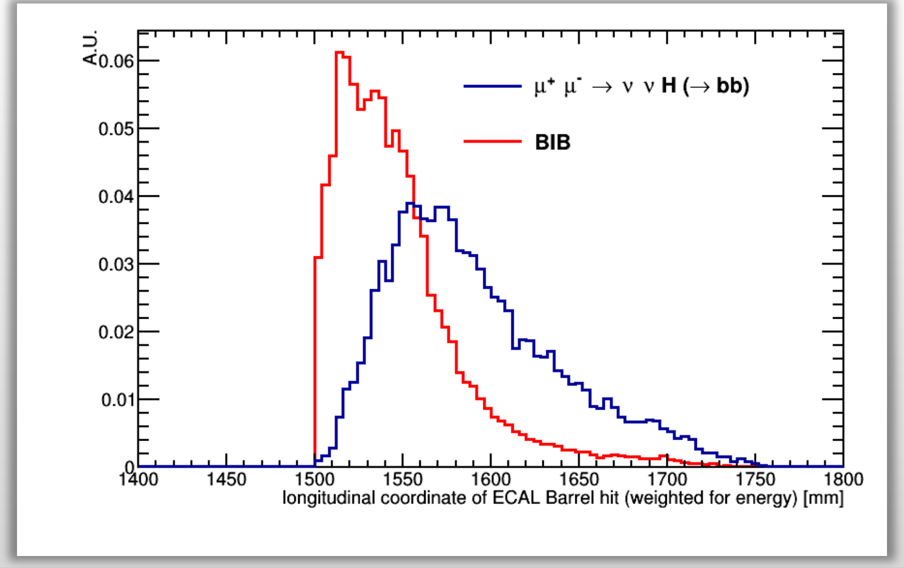


- New jet reconstruction algorithm based on particle flow is in progress.
- New jet b-tag algorithm based on machine learning methods under development.

ECAL barrel hit arrival time – t_0



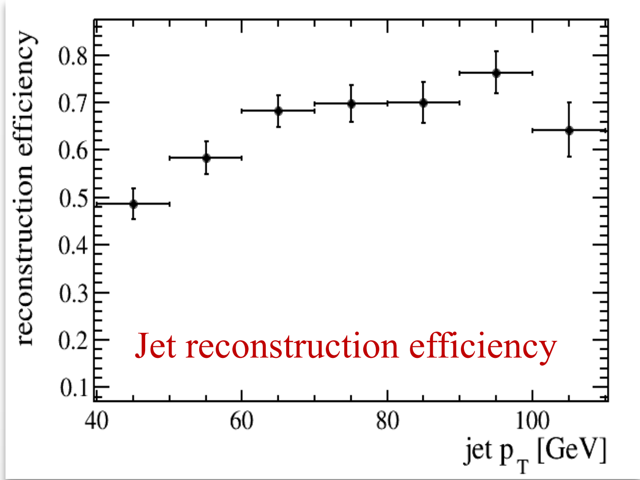
ECAL barrel longitudinal coordinate

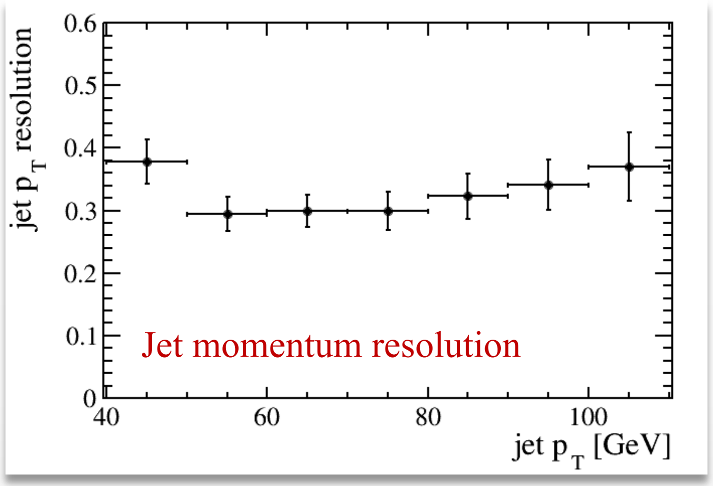


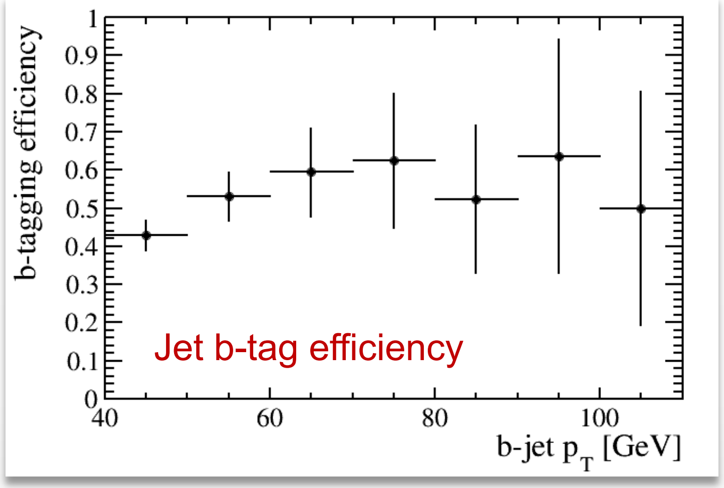
Jet Reconstruction and b-tag performance at $\sqrt{s}$ =1.5 TeV

Using the MAP detector and framework, performance have been determined using **simple and rough methods** for the reconstruction

L.Sestini M. Casarsa N. Bartosik L. Buonincontri







Background tagging:

- fake rate: 1 ÷ 3 %
- Tests show fake rate is manageable

CLIC with Machine Learning method is factor 2 better at 1.4 TeV

Higgs $b\bar{b}$ Couplings Results

- The instantaneous luminosity, $\mathcal{L}$, at different √s is taken from MAP.
- The acceptance, A, the number of signal events, N, and background, B, are determined with simulation.
- One detector and 4 Snowmass years are assumed.

$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

CLIC numbers are obtained with a model-independent multi-parameter fit performed in three stages, taking into account data obtained at the three different energies.

Results published on JINTST as Detector and Physics Performance at a Muon Collider

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- ❑ **Detector performance in the presence of the beam-induced background at different center-of-mass energy:**
  - **Selection of R&D that can be performed in synergies with the upgrade of existing experiments and new projects.**
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- ❑ Software framework to perform the studies:
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Detector Studies and Experiment Design

A new detector has to designed and optimized:

- Tracking system where position, energy and time resolution have to be pushed to the limit. What kind of technology is the most suited? What kind of shape and structure? New ideas?

- Calorimetry exploiting time information at least in the inner part is necessary. What kind of technology? What kind of design? New ideas?

- Muon system: would be possible to reconstruct and identify muons by using an integrated technique exploiting tracking + calorimeter and a “light” muon detector?

- Data acquisition: mandatory to reduce the BIB at data taking time as much as possible. Study new technology based on AI on new processors.

- Possible to design an experiment, maybe two with different specializations.

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Physics Performance

- New reconstruction algorithms for tracking, electron, muons, jet and displaced vertices identification are being developed following AI methods. New ideas?

- Create a list of physics benchmark processes to be study following two different paths:

  - Identify the physics process for which the full simulation is mandatory and study them including the BIB.

  - Use efficiencies and resolutions à la Delphes, whenever it is possible but "cum grano salis" to make sure biases are not create.

To conclude

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